



Sorghum Varieties Invariably Show Improved Water Use Efficiency Coupled with Morpho-physiological Characters under Limiting Water Conditions



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Abstract: Climate change has affected several aspects of sustainable food production and food security. One of the major challenges of climate change is the prolonged drought that has led to water stress in crops, including sorghum (*Sorghum bicolor* L. Moench), in arid and semi-arid areas of Kenya. A study was conducted at the Nadapal irrigation scheme in Turkana County, Kenya, to determine the crop's performance under different water application regimes. Principal component analysis was used to compare phenotypic and genotypic characteristics and to study ontogenetic morphological integration leading to variation in sorghum yields. A path coefficient analysis was applied to estimate correlations between yield and yield-related traits and to determine the direct and indirect effects of these traits on yield per plant. It also enabled the identification of causal factors and other overlapping factors. The experimental design was a randomized complete block design (RCBD) with three replicates. From the analysis of variance, a highly significant and positive strong correlation was observed for seed index and plant height ($r = 0.76$) as well as head weight and grain yield ($r = 0.74$). Surprisingly, water use efficiency (WUE) showed a negative correlation with all other measured parameters. These kinds of interactions amongst WUE and other yield components depend on whether greater WUE is associated with equivalent carbon gain while using less water or greater carbon gain while using equivalent amounts of water (or a combination of the two). The correlation and path coefficient analyses carried out demonstrated that head weight, head length, and seed index were important selection criteria for high grain yields in sorghum. There were direct and indirect effects of the parameters on sorghum yield. This study evaluated other important correlations among sorghum characteristics that breeders can exploit to enhance the production of high-yielding sorghum cultivars. It revealed overlapping characteristics among head weight, head length, and seed index in relation to grain yield. As a result, these components could serve as selection criteria to improve sorghum seed yield.

Introduction

Sorghum (*Sorghum bicolor* L. Moench) is an important crop in the arid and semi-arid areas due to its ability to endure water stress and tolerate drought (Amelework et al., 2016). In Sub-Saharan Africa, sorghum is ranked second after maize (Hadebe et al.,

2017; Pius et al., 2025; Eseroghene and Ikechukwu, 2018) and fifth globally as the most important cereal grain after wheat, maize, rice, and barley (FAOSTAT, 2017; FAO, 2018; Rashwan et al., 2021). In Kenya, it is economically ranked as the third most important cereal crop after maize (*Zea mays*) and wheat (*Triticum*



aestivum) (AGRA, 2013; Riziki et al., 2022; MoA, 2013) and is known to be well adapted to harsh climatic conditions (Kaaria et al., 2021). This property is crucial to better cope with the impacts associated with the changing climate (Obia, 2011; Mwadalu et al., 2022) and has a higher potential to enhance food security in marginal regions. Compared to other cereal crops, sorghum has a lower production cost due to its low input requirements during its growth. Sorghum is a regularly consumed food by over 0.5 billion people in over 30 countries, mainly in the developing world (Kumar et al., 2011; Mwadalu et al., 2021; Njinju et al., 2022; Pius et al., 2025). It is an extremely important crop for the poverty-stricken and food-insecure people and is predominantly grown in ASALs (USAID, 2010; Timu et al., 2012; Sharma et al., 2025). Apart from being used as human food, sorghum can be used to prepare feed for animals (Aruna and Visarada, 2019; Hassan et al., 2020), fuel, and building materials. The yield of this crop has been affected despite the introduction of newly improved varieties in Kenya (Muui et al., 2013). Furthermore, the yield is affected by climate change, which is catalyzed by the arable land shrinkage, depleting groundwater level, erratic rainfall patterns, and growing population (Maitra et al., 2024, 2025; Sairam et al., 2025). One of the important factors affecting the yields of this crop is the untimely and inadequate application of irrigation water needed for plant growth, leading to stress and poor performance. Severe water stress results in reduced photosynthesis, carbohydrate translocation, and even disturbance of metabolic processes (Bohnert and Jensen, 1996; Zaman et al., 2017; Nasar et al., 2022). In addition, farmers are still using unimproved varieties with poor growth characteristics, hence exacerbating food insecurity. Therefore, farmers can benefit when provided with genotypes with good performance in terms of yield characteristics, reducing problems of malnutrition. Plants, including sorghum, have developed different mechanisms to help cope with the alarming drought stress physiologically, biochemically, and morphologically through tolerance, avoidance, and escape (Khoyerdi et al., 2016; Wu and Zou, 2017; Carlson et al., 2020). The mechanism responses involve the production of signaling hormones such as salicylic acid, jasmonic, and ethylene and signaling network that involves intermediates reactive oxygen, cytosolic and hydrogen ions that activates physiological reactions such as reduction in leaf area, the closing of stomata, and reduction of cell turgor pressure as well as production of secondary metabolites (Ranjan et al., 2023; Goher et al., 2023; Carlson et al., 2020; Sagar et al., 2022; Okello et al., 2017). Previous

findings have shown decreased plant growth and yield components with reduced soil moisture content. This could be due to water deficiency that undesirably affected crop nutrition and physiological growth of crops, consequently leading to reduced and compromised yield potential in terms of size, biomass, yield containers, and crop quality (Aladenola and Madramootoo, 2014; Rahimi et al., 2023; Rossini et al., 2013; Syengo et al., 2019). Of significance, the observable reduction of the size of the plant and its components resulting from drought stress could also be attributed to low turgor pressure (Shao et al., 2008) that has the potential to suppress cell enlargement, division, and development of the crop (Manivannan et al., 2007). This has also been reported by Yaqoob et al. (2013), whose study showed that drought stress has a damaging and detrimental effect on all growth stages of chickpea. When selecting sorghum varieties for improved grain yield, the interaction between yield and other plant characteristics that enhance yield should be considered. The connectivity of some yield-enhancing characteristics is crucial during evaluation because the characteristics of yield components do not occur independently. Crop yield enhancement may be achievable by breeding its contributing components if the yield-enhancing traits are highly heritable and have a favorable association with ultimate yield (Majeed et al., 2023). In the literature, there has been a lack of or insufficient information on correlation-based path analysis and trait association of sorghum. The current study employed path coefficient analysis approaches to evaluate the relationships and the effect of significant yield contributing components on the yield of sorghum crops. This study aimed to identify the degree and nature of the correlation between grain yield and contributing components. These results can subsequently be used as selection criteria for increasing sorghum production in arid and semi-arid areas.

Materials and Methods

Site Description

The study was conducted at the Nadapal irrigation scheme in Loima sub-county, Turkwel ward, Nadapal location, Turkana County. The farm lies at a latitude of 30°60'20" N, a longitude of 35°51'55" E, and 1776 m asl. The experimental plot measured 5x5m. The soils of the experimental field are well-drained and moderately deep, sandy /silt/clay. The soil was composed of 60% sand, 30 % silt, and 10% clay. The pH of the topsoil is 7.6, while in the subsoil pH range is 7.4 to 8.5. In some spots, the subsoil is slightly saline, with an electrical conductivity of 19 mS/m. The soils are very low in organic matter,

with organic matter content less than 0.2%. The cation exchange capacity is 10 me/100mg in topsoil and 14 me/100mg in more clayey subsoils. The general soils are classified as cambisols, sodic, and partly saline. Weather data shows that the area experiences temperatures between 20 °C and 41 °C with a mean of 30.5 °C. The slope is less than 1% and the mean annual precipitation amounts to 500 mm per year on average, occurring mainly from June to September, and potential evaporation is greater than 2400 mm.

Experimental Design and layout

The experimental setup was a factorial arrangement in a Randomized Complete Block Design (RCBD) with three replications. Each plot measured 5 x 5m, separated by 1m wide paths. The block area was 15 x 5m, equivalent to 75 m², and a plot area of 5m x 5m, equivalent to 25m². Three sorghum varieties, Gadam, Turkana Local Variety, and Seredo, were used. The experiment consisted of three irrigation intervals of 7, 14, and 21 days. The local irrigation interval was used as the control interval (21 days). The irrigation amount was set to 70% of the field capacity.

Data collection

Six plants were tagged in each treatment in all the replicates and used for data collection. Parameters evaluated included plant height (cm), the weight of 100 seeds (g), head length (cm), head weight (g), straw weight (g), gross grain yield per plot (g), seed index (g), and water use efficiency. Grain yield per plot was determined at maturity by randomly selecting 10 plants in each plot. The heads were threshed and weighed to determine grain yield per plot (g).

Data analysis and presentation

The quantitative data collected from the study were subjected to a two-way analysis of variance (ANOVA) using R statistical software. Mean separation was done using Tukey's test (HSD) at a 95% confidence level. The Pearson correlation coefficient (r) was used to determine the degree of relationship between the quantitative characters. Principal component analysis (PCA) was also used to display relationships among the variables. This multivariate technique extracts the most crucial information from the data to display the patterns of similarity among observations and variables as points on maps. A path coefficient analysis was carried out to determine both the direct and indirect effects of the selected variables and to identify the interactions among various parameters and the gross yield.

Result

Mechanisms of Mulch and Compost in Soil Enhancement

Mulch: Functions and Mechanisms

There were significant differences in sorghum heights ($P \leq 0.001$) in different varieties (Figure 1). The highest plant height of 307cm was recorded in the Turkana local variety, followed by the Seredo variety (173 cm) and the Gadam variety (125 cm), which had the lowest plant height. There was no significant difference between the Seredo and Gadam varieties.

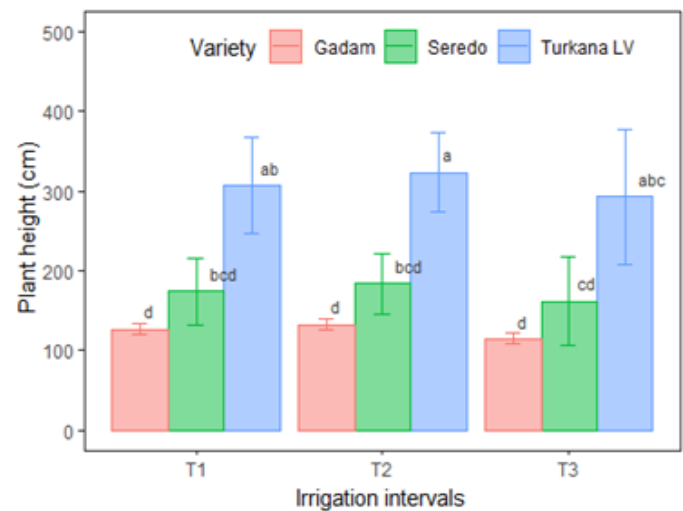


Figure 1. Effects of watering intervals on the plant height of three sorghum varieties: T1, 1 week interval; T2, 2 weeks interval; T3, 3 weeks interval.

Yield and yield characteristics

The results from the yield and yield characteristics analysis are presented in Table 1. There were significant differences in head length across sorghum varieties under different water regimes ($P \leq 0.001$). The highest head length was obtained in the Seredo variety under one (1) week watering intervals (32.6 cm), while the lowest reading was recorded in the Turkana local variety under three (3) weeks watering intervals (18.7cm). Significant differences in grain yield (kg) of the different varieties of sorghum under different water regimes ($P \leq 0.001$) were recorded. The highest grain yield was obtained in the Seredo variety under one (1) one-week watering interval (65.5kg), while the lowest weight was recorded in the Gadam variety under three (3) weeks watering interval (37.2kg). There were significant differences in the seed index across sorghum varieties under different water regimes ($P \leq 0.001$). The highest seed index was obtained.

in the Turkana local variety under two (2) watering intervals (42.1 g), while the lowest reading was recorded in the Gadam variety in three (3) week watering intervals (23.4 g). Significant differences in the yield of 100 grains (g) of the different varieties of sorghum under different water regimes ($P \leq 0.001$) were recorded. The highest yield of 100 grains (g) was obtained in the Seredo variety under a two (2) watering interval (8.07g), while the lowest reading was recorded in the Gadam variety in a three (3) week watering interval (5.67g). There were significant differences in head weight across sorghum varieties under different water regimes ($P \leq 0.001$). The highest head weight was obtained in the Seredo variety under one (1) watering interval (104 g), while the lowest reading was recorded in the Gadam variety in a three (3) week watering interval (51.0g). There were significant differences in straw yield among sorghum varieties under different water regimes ($P \leq 0.001$). The highest straw yield was obtained in the Seredo variety under one (1) watering interval (31.9g), while the lowest reading was recorded in the Turkana local variety in a three (3) week watering interval (16.4g).

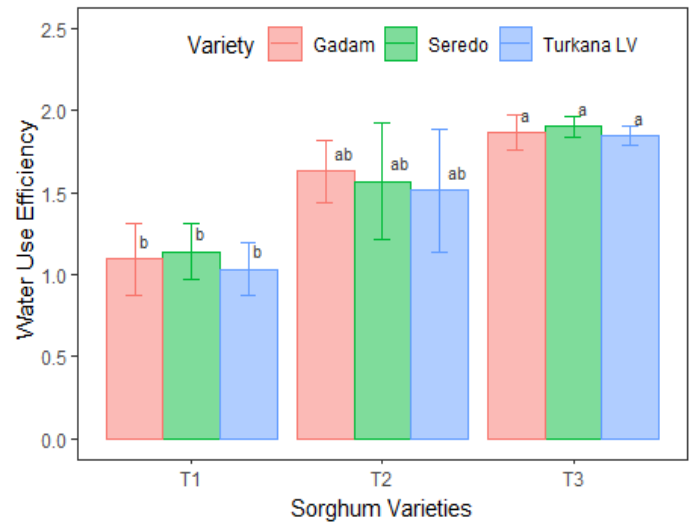


Figure 2. Effects of different water application regimes on water-use efficiency across sorghum varieties. T1, 1 week interval; T2, 2 weeks interval; T3, 3 weeks interval.

Correlations between quantitative traits.

Pearson correlation was used to determine the relationship between the variables, as shown in Table 2

Table 1. Effects of different water application regimes on the yield of different sorghum varieties.

Treatment	Variety	Head length (cm)	Grain yield (kg)	Seed Index (g)	Yield of 100 seeds (g)	Head weight (g)	Straw yield (g)
TL3	Gadam	19.2±3.43bc	37.2±3.28d	23.4±3.70d	5.67±0.962a	51.0±6.24c	19.4±5.71a
TL1	Gadam	23.6±4.04abc	46.2±3.61cd	24.1±3.85cd	6.56±1.14a	63.2±6.73bc	26.1±9.31a
TL2	Gadam	20.4±2.82bc	45.2±3.62cd	25.5±3.38cd	7.57±1.014a	62.2±8.50bc	24.9±3.78a
TL3	Seredo	26.4±5.40abc	50.6±3.43bcd	24.9±5.05cd	6.46±2.00a	80.4±21.0abc	17.9±3.25a
TL1	Seredo	32.6±4.67a	65.5±5.66a	27.2±5.55bcd	7.80±2.20a	104±7.51a	31.9±6.21a
TL2	Seredo	30.5±3.34ab	63.7±5.75ab	31.1±3.57abcd	8.07±1.33a	101±14.1a	28.3±6.67a
TL3	Turkana local	18.7±4.57c	45.2±3.62cd	37.9±7.26abc	5.78±0.529a	77.9±16.0abc	16.4±2.08a
TL1	Turkana local	20.9±3.79bc	54.7±4.41abc	40.9±5.84ab	6.53±0.865a	94.3±9.95ab	20.4±6.32a
TL2	Turkana local	20.6±3.85bc	48.4±8.34cd	42.1±4.76a	7.13±1.29a	83.5±9.55abc	19.6±5.37a
P value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter in each column are not significantly different at $P \leq 0.001$. T1= 1 Week interval; T2= 2 weeks intervals; T3= 3 weeks intervals.

Water use efficiency

There were significant differences in water use efficiency of sorghum plants ($P \leq 0.001$) as shown in Figure 2. There were significant differences in the interaction between different water regimes and the varieties of sorghum crops. The highest water use efficiency was obtained in 3-week watering intervals in the Seredo variety (1.9), with the lowest results being obtained in 1 1-week watering interval of the Turkana local variety (1.03).

and Figure 3. Both positive and negative significant ($p < 0.05$) correlations were reported between the quantitative variables that included plant height, head length, seed index, straw yield, yield of 100 grains, head weight, and water use efficiency. Water use efficiency was negatively correlated with all the parameters. There was a strong positive correlation between seed index and plant height ($r = 0.760215$) as well as head weight and grain yield ($r = 0.739975$). The plant height had a low positive

Table 2. Pearson's correlation coefficients between quantitative variables: Sindex, Seed Index; Pheight, Plant height; Hweight, Head weight; Gyield, Grain yield; Hlength, Head length; Yield, Yield of 100 grains; Syield, Straw yield; Wause, Water Use Efficiency.

	Pheight				Hlength	Gyield		Sindex	Yield	Hweight	Syield	Wause
Pheight	1											
Hlength	-0.18605				1							
Gyield	0.06143				0.652666	1						
Sindex	0.760215				-0.23292	0.157487	1					
Yield	0.035079				0.556163	0.417614	-0.14517	1				
Hweight	0.407139				0.522505	0.739975	0.306287	0.489641	1			
Syield	-0.30545				0.407589	0.437002	-0.1683	0.460713	0.234412	1		
Wause	-0.02971	-0.26256	-0.3701	-0.19409	-0.11737	-0.33961	0.34533	1				

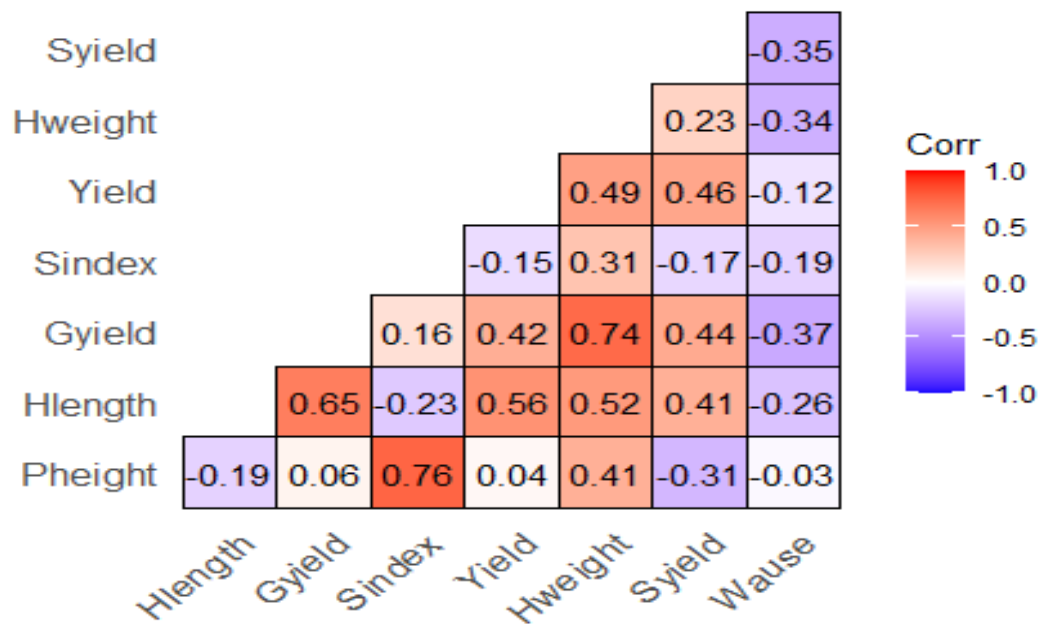


Figure 3. Pearson correlations of sorghum properties. The variation explained by each principal component is presented on the axes. Sindex, Seed Index; Pheight, Plant height; Hweight, Head weight; Gyield, Grain yield; Hlength, Head length; Yield, Yield of 100 grains; Syield, Straw yield; Wause, Water Use Efficiency.

Table 3. Phenotypic correlations: Spearman's correlation coefficients (upper right diagonal elements) and Pearson's correlation coefficients (lower left diagonal).

	Pheight	Hlength	Gyield	Sindex	Yield	Hweight	Syield	Wause
Pheight	1	0.01648	0.2350	0.7448****	0.1325	0.5720**	-0.1770	-0.07483
Hlength	-0.1860	1	0.5702**	-0.2253	0.4475*	0.5324**	0.3626	-0.2480
Gyield	0.0614	0.6527***	1	0.2344	0.2857	0.7381****	0.3663	-0.3903*
Sindex	0.7602****	-0.2329	0.1575	1	-0.1502	0.3199	-0.1630	-0.1787
Yield	0.0351	0.5562**	0.4176*	-0.1452	1	0.4377*	0.4316*	-0.0525
Hweight	0.4071*	0.5225**	0.7400****	0.3063	0.4896**	1	0.2039	-0.2770
Syield	-0.3054	0.4076*	0.4370*	-0.1683	0.4607*	0.2344	1	-0.2706
Wause	-0.0297	-0.2626	-0.3701	-0.1941	-0.1174	-0.3396	-0.3453	1

Sindex, Seed Index; Pheight, Plant height; Hweight, Head weight; Gyield, Grain yield; Hlength, Head length; Yield, Yield of 100 grains; Syield, Straw yield; Wause, Water Use Efficiency. ****Significant at the 0.0001 probability level; ***significant at the 0.001 probability level; **significant at the 0.01 probability level; *significant at the 0.05 probability level.

correlation with both the grain yield ($r = 0.04$) and grain yield per plot ($r = 0.046$); however, it showed a low negative correlation with water use efficiency ($r = -0.03$).

Determination of linear and non-linear correlation

The monotonic relationship was determined by Pearson's and Spearman's correlation coefficients, as presented in Table 3) were used. The results revealed that a few parameters had similar values across pairwise correlations, indicating linear relationships among traits. Monotonic (nonlinear) associations were reported when Spearman correlations were greater than Pearson correlations (Xavier et al., 2017).

Principal Component Analysis (PCA) and graphical models

The Pearson correlations' biplot representations of PCA were carried out as shown in Figure 4. The parameters projected in the same direction have similar properties, while those projected in opposite directions are antagonistic (Xavier et al., 2017). The direction and magnitude of the correlation between sorghum yield and other components are important for determining the important characteristics that may be implemented in the breeding programme as a crop enhancement approach to improve the yields. From the initial results of eigenvalues, PCA extracts two components that explained about 90% of the cumulative variance contribution rate.

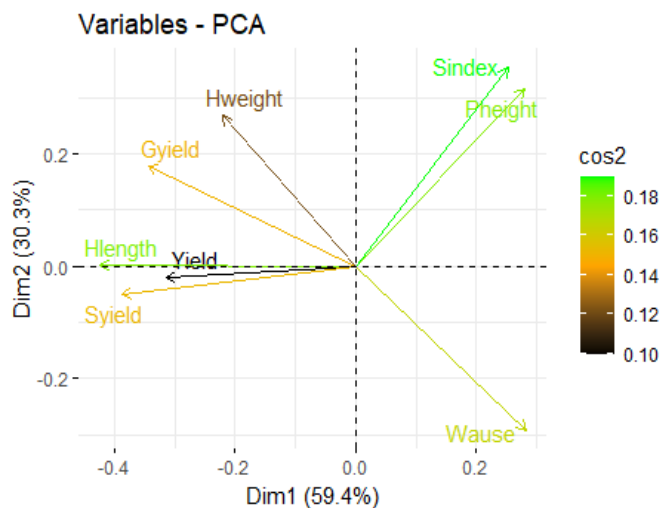


Figure 4. Principal component analysis of Pearson correlations of sorghum properties. The variation explained by each principal component is presented on the axes. Sindex, Seed Index; Pheight, Plant height; Hweight, Head weight; Gyield, Grain yield; Hlength, Head length; Yield, Yield of 100 grains; Syield, Straw yield; Wause, Water Use Efficiency.

Contribution of each variable

The Cos2 shows how much each variable is represented in a given component (A low value means that that component does not perfectly represent the variable, while a high value, on the other hand, means a good representation of the variable on that component). The direction of the arrow indicates the positive or negative correlation between the variable and the principal component. Seed index and Plant height show the same direction, indicating a positive correlation; however, head weight and water use efficiency point in opposite directions, indicating a negative correlation. Longer arrows show variables that contribute more to the variation in the data along that principal component. Small angles suggest a high positive correlation, while large angles suggest a negative correlation.

Path coefficient analysis

Path coefficient analysis was conducted to assess the direct and indirect relationships among the variables, as shown in Figure 5. Path coefficient analysis was carried out to determine the interactions among various parameters (direct and indirect correlations) and overall grain yield using a multiple linear regression model. It gives a clear evaluation of the cause-and-effect relationship. In this study, the assumption was made that multiple independent variables affect the overall yield of sorghum crops; therefore, yield is considered the artifact of all other parameters. According to the results of the path analysis (Figure 5), head weight had the greatest direct effect on yield (kg per hectare; 0.60). The table shows that sorghum grain yield is strongly dependent on head weight and head length and weakly dependent on water use efficiency and seed index. The yield of 100 grains is strongly reliant on head weight. The path coefficients (standardized regression coefficients) for Grain yield and Head weight (0.60***) and Grain yield and Head length (0.33*) were reported to be significant and positive. However, plant height had the highest direct negative effect on grain yield (Table 2). Plant height had the highest indirect influence on yield kg per hectare (0.788). These characteristics, however, can be used to develop an ideal selection index to improve sorghum yield.

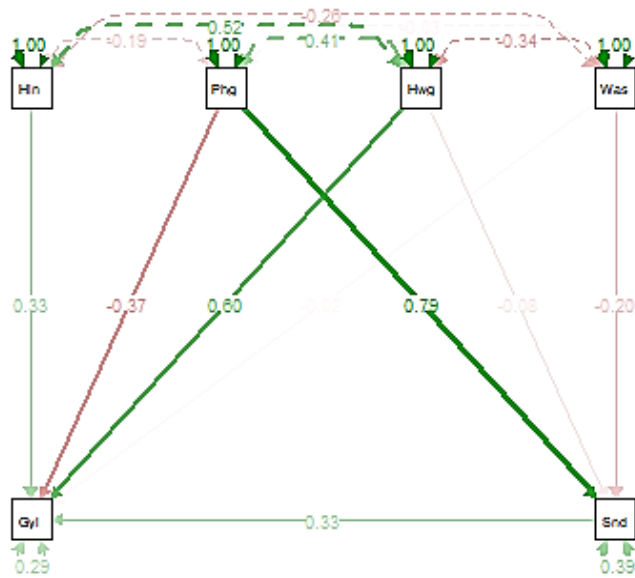


Figure 5. Path coefficient diagram representing cause and effect relationships among quantitative characteristics and grain yield. The green single arrowed lines in the path diagram reflect direct effect, whereas the cream arrowed lines reflect mutual connection. Note: Snd, Seed Index; Phg, Plant height; Hwg, Head weight; Gyl, Grain yield; Hln, Head length; Was, Water Use Efficiency.

Discussion

The varieties differed significantly in height, and this could be attributed to their genetic makeup. The Turkana local variety is naturally tall and has not undergone any improvement process to modify its height, and therefore, it recorded the highest height among the three varieties. Gadam is a dwarf sorghum variety that tolerates low rainfall of about 200 mm and matures in two and a half to three months (Esipisu, 2011; Pius et al., 2025). The Gadam sorghum variety was introduced by KARI to the semi-arid Eastern Kenya in 2009 as a way for farmers to improve their food security and earn some income for their livelihoods. The findings are in agreement with the KARI 2009 results that established the height of the variety to be 100-130 cm. The results from the Seredo variety were also around the variety attribute of 150-160 cm. This is because of the breeding process that lowered its height. From the results, all the varieties gave higher grain yields, head lengths, head weight, and straw yields when irrigated after a one-week interval. This can be due to the decrease in moisture stress due to sufficient soil moisture from watering (Heydarzadeh et al., 2021; Cheptoeck et al., 2021). Water is required during the important stages of plant growth, such as tasseling and grain filling. In all the varieties, watering after three-week intervals gave lower results due to an increase in soil moisture stress. These findings corroborate those of Cao et al. (2003), who reported that irrigation frequency can

change the spatial distribution of soil moisture and soil-water storage. Low-frequency water application (once every 3 weeks) favored water infiltration to lower soil layers where the plant roots could not reach, and thus surface soil moisture was lower. High-frequency water application (once every 1 week) is conducive to a uniform distribution of water in the soil profile (Liu et al., 2013). Water use efficiencies for sorghum at different water regimes, as presented in Figure 2, showed that the highest water use efficiency of 1.9 was obtained when the Seredo variety was irrigated after a three-week interval, while the lowest value of 1.03 was obtained from the Turkana local variety irrigated after a week interval. These results indicated that the water use efficiency was increased when the water application intervals increased. The strong positive association of seed index and plant height suggested a concurrent increase in the weight of 1000 seeds as the plant height increased. This correlation between seed index and plant height is supported by the findings of Xavier et al. (2017), who reported a concurrence of residual and genetic correlations, which was associated with high phenotypic correlations. In addition, the positive association between seed index and head weight could be helpful when selecting cultivars with larger seeds since previous reports found that seed size is also positively associated with yield (Cicek et al., 2006; Maestri et al., 1998). It might be because the reproductive period was more sensitive to precipitation than the vegetative period. The correlation coefficient between sorghum yield and water use efficiency in this study was negative. This may be attributed to insufficient water during the grain-filling stage. This negative correlation was also due to other environmental factors, such as temperature and heavy rainfall experienced in the area during the grain-filling stage. This is in agreement with the findings of Liu et al. (2013a, b, 2015); Hou et al. (2014), who also reported that grain yield can also be affected by other climatic factors such as temperature. In a study by Guoju et al. (2013a), it was reported that the water use efficiency of wheat, maize, and potato increased over the past 50 years due to an increase in temperature and a decrease in precipitation. In a similar study, Guoju et al. (2013b) also reported a linear decrease in the WUE as the amount of annual rainfall increased above 310 mm. The effects of low temperatures could have also led to low water use efficiency and an increase in plant parameters. Under low temperatures, the evaporation is low, and higher water use efficiency sets in, which may lead to low yields (Nyawade et al., 2021; Maina et al., 2025; Ray et al., 2025a). This finding is in agreement with those of Condon et al. (2004) and Blum

(2009), who found that higher WUE that occurs due to a low evaporation significantly reduced yields in crops, which they attributed to excess water in the growing conditions. From the observed interaction between WUE and drought stress, it implies that these variables' impacts depend on whether greater WUE is associated with equivalent carbon gains while using less water or greater carbon gain while using equivalent amounts of water (or a combination of the two). Therefore, maintaining equivalent carbon gain while using less water can create the potential for drought stress tolerance if the unused water remains stored in the soil for subsequent access and use (Leakey et al., 2019; Zeqiang et al., 2025; Jamal et al., 2025; Rahimi et al., 2022). Consequently, achieving greater carbon gain while using equivalent amounts of water can create the potential for greater productivity without increasing the risk of drought stress. However, as others have been at pains to point out (Blum 2005; Condon et al., 2004), the potential for greater WUE that leads to enhanced productivity and yield is not always met, which agrees with negative WUE and other yield parameters in our current findings. In a nutshell, two distinct syndromes of whole-plant response downstream of having greater WUE can negate the potential benefits of greater WUE. Again, there is a tight link between environment and total biomass production under all environmental conditions (Blum, 2009; Ngugi et al., 2022). This is also supported by a study by Hatfield et al. (2011), who in their study showed an existing interaction between the climate with changes in phenology, growth, yield, and water use of crops. Climate change has been reported to have an impact on the radiation use efficiency of crops, which is related dynamically to plant growth (Mukesh et al., 2024; Ray et al., 2025b; Maheswari et al., 2025). In general, WUE increases with an increase in temperature until the optimum temperature is reached, then starts to diminish when it becomes too hot (Allen et al., 2003). This is dependent on the crop. Straw yield had a significant positive correlation with head length, grain yield, and yield of 100 grains. There was high vegetative growth in the sorghum varieties that were under the control of the genes. This finding is in corroboration with that of Takamizo et al. (2012)- who also reported that the vegetative growth stage in sorghum is a component of the genetic makeup of the crop, which can be influenced by daylight length.

There was an observed negative correlation between the seed index and the head length. This was attributed to the fact that the sorghum with longer head lengths showed a decreased size of the grains. The increase in head length was accompanied by a decrease in seed size,

and therefore the seed index (weight of the 1000 seeds) simultaneously decreased. There was a high grain-filling percentage reported in this study, which was dependent on the sorghum panicle length, and the high gave a greater number of grains per panicle, which resulted in the low grain weight. Our results indicated that the grain sizes were more plastic and depended on the head length, which was in agreement with the findings of Tao et al. (2021). The higher the seed number, the lower their weight will be, and this was in line with the findings of Yang et al. (2010) and Nasar et al. (2025), who realized a tremendous increase in photosynthesis in panicles with fewer seeds, leading to an increased weight. These results contradicted the findings of Shinda et al. (2021) significant negative correlation was observed between the grain filling percentage and panicle length, together with the weight of a thousand seeds. The head length is to a great extent under genetic control but can also be influenced by water uptake during the grain-filling stage (Borras et al., 2004; Priyadarshani et al., 2025; Jamal et al., 2024; Gambin and Borras, 2005). These findings did not agree with those of Shinda et al. (2021), who indicated that a high seed index (weight of 1000 seeds) is positively correlated with head length. Grain yield gave a positive, non-significant phenotypic correlation with plant height ($r = 0.0614$) and a strong, significant positive correlation with head weight ($r = 0.7381^{****}$). Ezeaku and Mohammed (2006) also reported similar findings, where a high positive phenotypic correlation coefficient of grain yield with plant height and head weight was observed. Grain yield showed a positive phenotypic correlation with panicle yield per plant ($r = 0.729$) and harvest index ($r = 0.599$). Therefore, the positive association of grain yield with these traits suggested the possibility of simultaneous improvement of grain yield through indirect selection of these positively correlated traits. The positive association between all possible pairs of traits suggested the possibility of correlated response to selection, so that with the improvement of one trait, there will be an improvement in the other positively correlated trait. The positive genotypic association allows simultaneous genetic improvement for grain yield.

Unlike a positive correlation, a negative correlation between two desirable traits may impede or make it impossible to achieve the simultaneous improvement of those traits along with each other. Generally, the existence of a strong positive correlation between grain yield and other traits helps in identifying traits that could be used for indirect selection for the improvement of grain yield. However, the negative correlation indicated that some environmental variables that are favorable for

the increment of the value of one trait might have caused a value decrement of negatively correlated traits. In sorghum, plant height was negatively correlated with straw yield. This finding was in agreement with the work of Felderhoff et al. (2012) and Burks et al. (2015), who reported a strong correlation between the plant height and the biomass yields in sorghum plants. Plant height affects the internode lengths, and therefore, an increase in plant height increases the internode lengths. This leads to fewer leaves per plant and thus lower straw yield. The differences in the plant height could be a result of the genetic and environmental factors during the growth period of the plant (Liao et al., 2019). These yield characteristics of sorghum are important during selection and breeding purposes to enhance the grain yield (Ali et al., 2011; Reddy et al., 2013).

Conclusion

There was observed significant relationships were observed between different parameters and the yield of sorghum crops. The data obtained from this study indicated that sorghums do not have to be tall in order to have a higher straw yield, as this is fully dependent on the internode lengths that determine the number of leaves. The path coefficient analysis helped to identify the influence that other parameters had on the grain yield. This information is important for breeding purposes because it identifies both the direct and indirect influence of other factors on the yield. Therefore, the parameters that had a direct positive correlation with grain yield can be considered during breeding to improve the yields. To directly improve the sorghum grain yields, breeding that targets the head weight should be conducted.

Conflict of Interest

The authors declared no conflict of interest with regard to this publication.

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